Multimode fibers in Millimeter-wave evolution for 5G cellular networks

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ABSTRACT

Small-cell and cloud-RAN systems along with the use of the millimeter-wave band have been considered as promising solutions to meet the capacity demand of the future wireless access networks. Radio over Multimode fibers (RoMMF) can play a role in the integrated optical-wireless access systems for next-generation wireless communications, mainly in within-building environments. The numerical results show the effectiveness of MMF to transmit at 60 GHz band with 7-GHz bandwidth for different link lengths and refractive index profiles under restricted mode launching and using narrow linewidth sources. The integration with optically powered remote antenna units is also proposed based on the large core effective area of MMF. Temperature impairments and graded index plastic optical fiber transmission are also discussed.

Keywords: RoMMF, mm-wave cells, multimode fibers, GIPOF, transversal filters

1. INTRODUCTION

The explosion of mobile traffic fosters 5G (5th Generation) cellular network evolution to increase the system rate around 1000 times higher than the current systems in 10 years and to manage the expected monthly global mobile data traffic that will surpass 24.3 exabytes by 2019 [1]. Motivated by this scenario and in order to avoid capacity shortage, there are several studies to integrate mm-wave access into current cellular networks. Some of them include mm-wave small cells base stations (BS) and a conventional macro base station connected to Centralized Radio Access Networks (C-RAN) to efficiently operate the system, and using up to 7 GHz of continuous spectrum available worldwide at the 60GHz unlicensed band [2]. Wireless backhaul and access are proposed in those small cell networks and measurements of system bandwidth in excess of 500 MHz at 28 GHz are reported [3]. Fiber-optic networks can also be used as mobile backhaul/fronthaul networks for conventional macro-cells and emerging small-cell cloud-RAN systems to meet the capacity demand of those future wireless access networks [4]. One challenge of cloud-RAN deployment is the cost and availability of fiber-optic backhaul/fronthaul networks that connect many remote antenna units (RAUs) with the digital baseband processing units (BBU) pools, mainly in the small-cell environment. Fiber-optic access networks, namely Fiber To The x (FTTx) provide very-high-speed services and can be deployed using different technologies, such as Time Domain Multiplexing (TDM), Time-shared Wavelength Division Multiplexing (TWDM), SDM (Spatial Division Multiplexing), Wavelength Division Multiplexing (WDM) Passive Optical Networks (PONs). All the former PON systems can be used as high capacity fronthaul/backhaul networks for high speed wireless access based on small cells and mm-wave radio.

Radio over multimode fiber technologies have been proposed in-building networks [5] for the distribution of optical wireless communication cells [6] as well as in broadband access networks [7], [8]. Temperature impairment characterization has also been analyzed over the broadband transmission bands that can be present in the frequency response of multimode fiber (MMF) are to support multiple-GHz carriers delivering schemes [9]. Measurements of

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Broadband Access Communication Technologies X, edited by Benjamin B. Dingel, Katsutoshi Tsukamoto, Proc. of SPIE Vol. 9772, 97720F · © 2016 SPIE
CCC code: 0277-786X/16/$18 · doi: 10.1117/12.2216107

perfluorinated graded index plastic optical fibers (PF-GIPOF) transfer function are presented in [10] highlighting the conditions upon which broadband transmission in regions far from baseband is possible, together with the model to describe this performance. From this model, different multimode fiber approaches are described in this paper, with the purpose of creating a cost-effective fronthaul alternative for mmwave-based small cells in 5G cellular networks, as multimode optical fibers can be used to feed the different small cells base stations in some cases.

2. MULTIMODE FIBER TRANSMISSION

In this section a closed-form analytic expression to compute the baseband and RF transfer function $H(\Omega)$ of a MMF link (with fiber length *z*) that includes the influence of the third-order chromatic dispersion parameter β_o^3 and based on the electric field propagation method is briefly presented. For a deeper comprehension works reported in [11-12] are recommended.

The RF transfer function of a MMF link is given by:

$$H(\Omega) = \sqrt{1+\alpha_C^2} \cdot F(\Omega) \cdot \cos\left(\frac{1}{1+j\cdot a} \cdot \frac{\beta_o^2 \Omega^2 z}{2} - \arctan(\alpha_C)\right) \cdot \sum_{m=1}^{M} 2m(C_{mm}\chi_{mm} + G_{mm}) e^{-2\alpha_m z} e^{-j\Omega\tau_m z} \tag{1}$$

being

$$F(\Omega) = e^{-\frac{\Omega^2 \alpha_C^2}{8} \cdot \frac{a^2}{1+a^2}} \cdot e^{-\frac{b^2}{1+a^2}} \cdot \left(1+a^2\right)^{-1/4} \cdot e^{-\frac{j\arctan(a)}{2}} \cdot e^{-j\frac{\Omega^2\alpha_C^2}{24} \cdot a \cdot \frac{4+a^2}{1+a^2}} \cdot e^{jb\frac{a}{1+a^2}}$$
$$a = \frac{\Omega \beta_o^3 z}{\sigma_C^2} \quad ; \quad b = \frac{\left(\Omega \beta_o^2 z\right)^2}{2\sigma_C^2} \tag{2}$$

where Ω represents the frequency of the RF modulating signal, α_C the source chirp, and σ_C the source coherence time directly related to the source linewidth, respectively. Second- and third-order chromatic dispersion parameters have been assumed to be equal for all the modes guided by the fiber. The summation term represents a microwave photonic transversal filtering effect in which each sample corresponds to a different principal mode group (PMG) *m* carried by the fiber and in which the coefficients C_{mm}, χ_{mm} and G_{mm} stand for the light injection efficiency, mode spatial profile impinging the detector area, and mode coupling coefficient, respectively. This last term denotes that the periodic frequency response of transversal filters could permit a transmission capacity increase in such links, and results show that MMFs offer the potential for broadband transmission far from baseband through the presence of high-order resonances as well as flat regions in the frequency response in the microwave and millimetre-wave. Parameters α_m and τ_m represent the differential mode attenuation (DMA) effect, which causes the attenuation coefficient to vary from mode to mode, and the delay time of the guided modes per unit length, respectively. The $F(\Omega)$ term corresponds to a mode-independent term that depends on both the second- and third-order chromatic dispersion parameter.

3. MULTIMODE FIBER FOR 5G CELLULAR NETWORKS

The basic concept of cloud- RAN is to separate the digital baseband processing units (BBUs) of conventional cell sites, from the remote antenna units/remote radio heads (RAUs/RRHs), and to move the BBUs to the "cloud" for a centralized signal processing and management. Among others, novel architectures such as cloud-RoF access networks where cell sites are simplified to RAUs, and most functions are shifted to the BBU, are under study. Those cloud-RoF systems are capable of delivering different generations of wireless techniques carried on different radio frequencies in a shared infrastructure. The band-mapped mm-wave RoF scheme [4] fully utilizes the wide 7-GHz bandwidth centered at 60 GHz, and divides it into several subbands to deliver band-mapped existing services and high-speed data services in separate corresponding sub-bands. Therefore, only the spectrum around 60 GHz is modulated and transmitted in the fronthaul link. This unlicensed band varies slightly around the world, see Fig.1.a.

On the other hand, different operators can coexist and share a broadband fiber access infrastructure. Fiber-optic networks can be used as high capacity fronthaul/backhaul networks for high-speed multimedia access services and, at the same time, high speed wireless access based on small cells and mm-wave radio. The convergence of both fixed and wireless access networks happens in both indoor and outdoor environments. MMF is predominatly used worldwide [13] over single mode fiber (SMF) for indoor links up to 300 m and offers easier installation in within-building environments compared to SMF, due to the large core diameter of MMF fibers (typically 50 or 62.5 µm). This is the reason MMF fibers are envisioned in this paper to be part of Converged Fiber-Wireless Access Networks (see Fig. 1.b). Specific requirements on MMF are also described in ARINC 802 specifications intended to provide standardization of fiber-optic cables for the air transport industry.

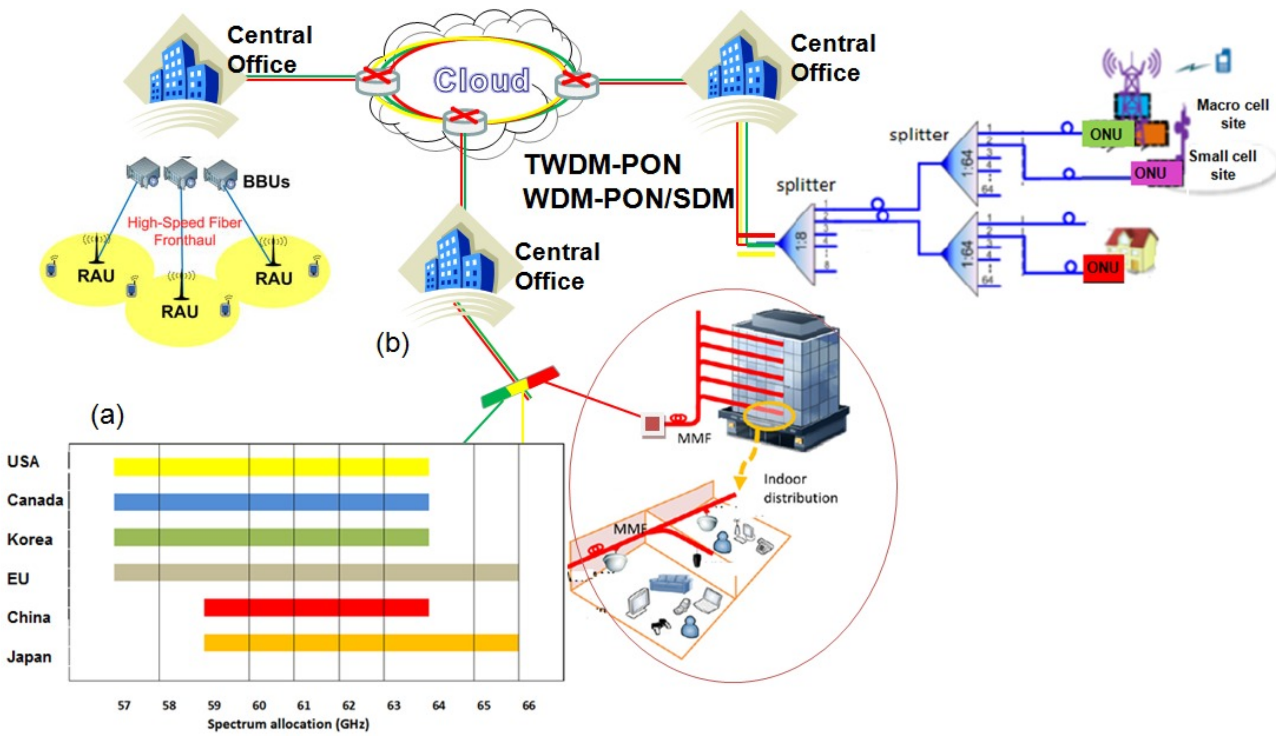

Figure 1. (a) 60-GHz millimeter-wave band. (b) Converged fiber-wireless access network scenarios including MMF.

3.1 Simulations

Theoretical simulations are developed with regard to different parameters affecting the MMF frequency response in order to determine the optimal conditions to transmit at higher frequencies than baseband, such as 60 GHz band with 7-GHz license-free bandwidth (see Fig. 1.a), for access links with small-cell BS. The feasibility of using MMF transmission at those high frequencies and short distances to provide point to point connections between BBUs and RRHs in small BSs and in within-building or aircrafts environments is analyzed.

A 62.5/125 µm graded-index (GI) multimode fiber with SiO_2 core doped with a 6.3 mol-% of germanium (GeO_2) with intrinsic attenuation of 0.2 dB/km@1550nm is considered. The graded refractive index profile has been approximated by the well-known power law equation and the core and cladding refractive indices have been approximated using a three-term Sellmeier function. The mode coupling coefficient G_{mm} is defined by a Gaussian autocorrelation function with a rms deviation of $\sigma = 0.0009$ and a correlation length of $\varsigma = 115 \cdot a$, being a the fiber core radius. It has been assumed a chirp-free source. DMA effects have been simulated by using the empirically function reported in [14], setting parameters $\rho = 9$ and $\eta = 7.35$, respectively. Two different light injection conditions are performed: overfilled launch (OFL) condition, in which all the principal mode groups (PMG) supported by the fiber carry the same optical power, or restricted mode launch (RML) by exciting different and specific set of PMGs. Mode converters can be used to excite the desired modes in GI-MMF [15] under RML.

Fig. 2 shows the silica-based GI-MMF frequency response dependence on the refractive index profile, α, from Eq. (1), under RML condition. A link length of 150 m and a Distributed Feedback (DFB) laser operating at 1550 nm with 10MHz of rms linewidth have been considered.

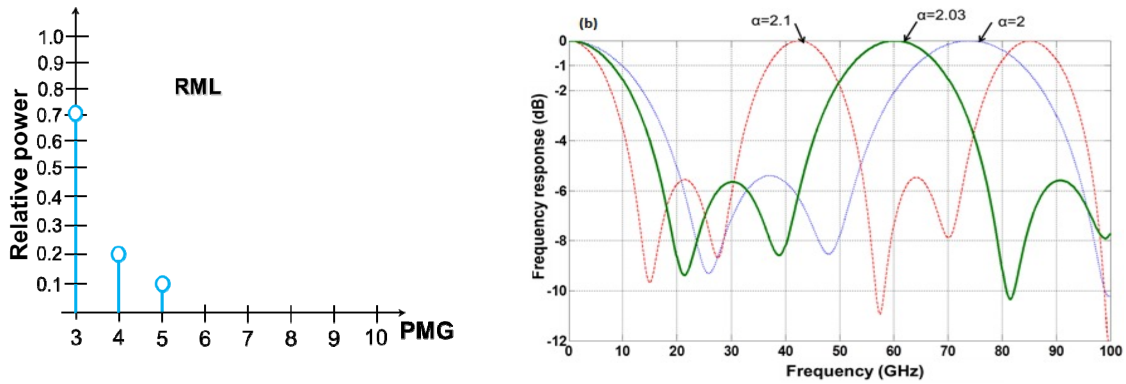

Figure 2. (a) RML details, first 3 Principal Mode Groups (PMG) are excited (b) 150m-long GI-MMF frequency response with different refractive index profiles at 1550nm.

For α=2.03, less than 1 dB attenuation around 60 GHz is obtained for a frequency range Δf=[52.3 GHz – 68.3 GHz], obtaining a 1-dB bandwidth of 16GHz. For that link length if α>2 both the baseband bandwidth and 1-dB bandwidth around the high-order resonances are decreased being their peak resonance shifted to lower frequency values around 45 GHz. On the other hand if α<2 both the baseband bandwidth and 1-dB bandwidth around the high-order resonances are increased being their peak resonance shifted to higher frequency values around 75 GHz. For the best case with α=2.03, if OFL is considered, it is possible to have a resonance around 60 GHz but with a 1-dB bandwidth lower than that obtained at RML condition. If now we modify the link length up to 275 m for α=2.03 at 1550nm, a 9 GHz 1-dB bandwidth can be obtained but the resonance peak is shifted. The maximum at 60 GHz is now reached with α=2.1. There is a direct relation between peak resonance frequencies, refractive index profile and link length. The 60 GHz resonance peak for different MMFs with the same refractive index profile can be provided using fiber lengths that are multiples of the designed length, see Fig. 3. For α=2.03 at 1550 nm, a link length of 300 m has a 1-dB bandwidth of 7.8 GHz ranging from 56.3 to 64.1GHz.

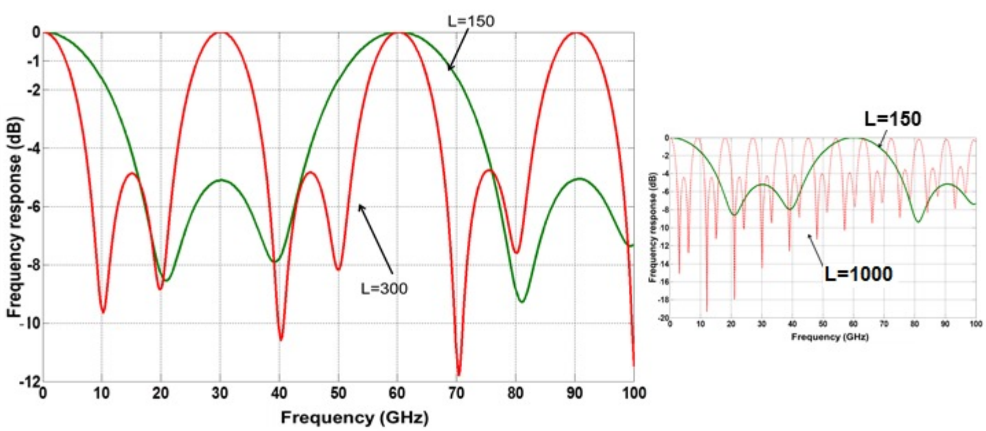

Figure 3. GI-MMF frequency response, at 1550 nm, α=2.03, RML and link lengths: L=150 m, L=300 m & L=1000 m.

This increase in length does not imply a high impact in the power budget of the system in a fiber with an attenuation of 0.2dB/km. As previously reported, any channel from WDM-PON or TWDM-PON can be used for transmission in a

MMF section, so the transfer function has been simulated for different C-band channels and almost no difference were appreciated.

3.2 Power over fiber integration

MMF with larger core effective area than SMF can transport higher optical power energy before non-linear effects such as stimulated Brioullin scattering appear and MMF transceivers are much less expensive than those used with SMF.
MMF can also be used as mobile fronthaul in small cells, where short reach connections are required between BBU and Remote Radio Units (RRUs) in a mobile Base Station. A first approach to estimate the required power on those small cell RRUs is based on considering the HetNet requirements on optical power transmission [2] and assuming that optical power is around 10% of total power consumption in current micro/macro 3G/LTE BS. Optical transmitter powers of 10dBm and 46dBm are required in small cell and macro BSs respectively. This means a scaling factor 1/1000, so from current Remote Radio Units consuming around 340W it can be expected to develop RRUs with a power consumption of around 340mW. Even keeping the current design with 3 RRUs per BS a total power of around 1W will be required. Power over fiber (PoF) technologies providing an electrical power of 0.5 W at 100 m using a double-clad fiber with a multimode inner cladding and power delivery efficiency of 15% for optically powered RAUs are reported in [16]. The latter can operate without external electrical power supply so they can be easily installed at any location. In our system, we propose using the same fiber for powering and transmitting data; power signal operates at 850 nm, meanwhile 5G signal optical carrier is at 1550 nm.

3.3 Discussion

Some measurements showing MMF propagation capabilities beyond baseband bandwidth at long link lengths have been reported along with temperature impairment characterization over the broadband transmission bands [9]. The thermal coefficient of around $1.5\times10^{-5}\,{}^{o}C^{-1}$ for the core and cladding refractive indices, respectively, reported by several authors have a negligible influence on the frequency response (and so on the high-order resonances) for a temperature range from 20 to 80 ºC. In contrast, for a similar temperature range, deviations of around units (in percentage from the nominal value) of the graded index exponent α, due to the influence of temperature on the silica properties, have been reported [17]. Consequently, this effect needs to be characterized due to the dependence of the MMF frequency response on the graded index exponent profile tolerances.

Multimode fiber infrastructure based on GI-POF can also be a solution in short reach scenarios. Some simulations of the PF-GIPOF transfer function have been performed from the model presented in this work. It is also possible to design links based on PF-GIPOF with 62.5µm core diameter, 1300 nm narrow linewidth source, 50 dB/km, both under OFL and RML conditions able to transmit around the 60 GHz band with the required 1 dB bandwidth, but as higher losses are expected shortest links should be considered. An optimum design with α =1.94 and 150 m link length is obtained. Parameters such as refractive index profile, core radius, link length, source central wavelength and linewidth should be considered to get a peak resonance at the desired central frequency of 60 GHz. Launching conditions are more related to bandwidth and are less determinant in PF-GIPOF designs versus silica based GI-MMF transmission.

4. CONCLUSIONS

MMF is proposed as part of the infrastructure to be used in Converged Fiber-Wireless Access Networks on future 5G cellular networks with small-cell BS to alleviate the challenge of small cell deployment in terms of cost. Additionally, it can provide a fiber-optic-based fronthaul network capable of connecting many small cell remote antenna units in both indoor and outdoor environments. Transmission capabilities at 60 GHz band with 7-GHz bandwidth for different link lengths and refractive index profiles are shown under RML condition and employing narrow linewidth sources. The integration with optically powered remote antenna units is also proposed based on the larger core effective area of MMFs. The link length can be adapted to get the 60GHz band for different GI-MMF refractive index profiles. Some discussion about the temperature influence and potential use of PF-GIPOF are also included.

5. ACKNOWLEDGEMENT

This work has been sponsored by the Spanish institutions Ministerio de Economía y Competitividad under project TEC2012-37983-C03-02, and grant S2013/MIT-2790-SINFOTON-CM.

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